SIMULATION AND ANALYSIS OF ASSESSMENT PROCEDURES FOR CONDITION BASED MAINTENANCE OF MV/LV SUBSTATIONS

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ABSTRACT

The application of condition based maintenance can reduce maintenance costs while maintaining a high standard of reliability because equipment is maintained only when the condition implies urgency. Commonly the equipment's condition is rated by subjective choice of maintenance personnel. An optimal maintenance planning needs objective condition assessment methods. In this paper, the parameterisation of two different assessment methods for MV/LV substations is introduced. These methods are applied in an asset simulation for condition based maintenance to analyse their influence on maintenance costs and failures. The simulation shows the influence of the assessment methods on failures and costs at different maintenance planning strategies.

INTRODUCTION

Simultaneously increasing cost pressure and the installation of new equipment like voltage regulated MV/LV transformers demands savings in the field of distribution grid operation. The implementation of a condition based maintenance strategy promises low costs while maintaining high standards of reliability because equipment is maintained according to its technical condition [1]. The reduction of unnecessary maintenance measures leads to a direct saving of network operating costs. Especially for new equipment without experience in maintenance cycles, the condition based scheme promises accurately timed measures, based on inspections and diagnostics.

It is however necessary to perform an accurate planning of maintenance measures to prevent decreasing reliability. Within condition based maintenance, the selection of maintenance measures bases on a condition value that leads to a rank of equipment. In practical applications, condition assessment procedures (CAP) are based on subjective rating and aggregation of indicators. There is a lack of objective procedures for the parameterization of CAPs that enable distribution system operator to evaluate the required intensity of maintenance for cost effective planning of measures. The high number of different electrical substation designs and upcoming installation of new equipment demands a procedure for automatic parameterization that accounts for a design specific condition assessment.

In this paper a methodology for objective parameterization of a common CAP, the weighted summation, is developed and compared to another common method, the ABC-methodology. To investigate the influence of different parameterizations and assessment methods, a condition based asset simulation is developed that simulates the effect of condition based maintenance on maintenance costs and failure rates.

CONDITION ASSESSMENT PROCEDURES

Common CAPs for MV/LV substations use inspection protocols as input. The protocols used for the investigation comprise of 70 items, divided into the six main components "building's inside and outside", "medium voltage switchgear", "medium voltage cable", "transformer" and "low voltage switchgear", that evaluate the equipment's condition by a rating between 1 and 4 [2]. The meaning of ratings is shown in table 1.

Tab. 1: Rating of equipment failures [2]

rating	interpretation
1	no visual failure
2	long-term maintenance required / no action required until next inspection
3	short-term maintenance required
4	immediate maintenance required

Two common CAPs are used to analyse the influences of the parameterizations on costs and failures. The ABC-procedure divides equipment into classes with varying priority for maintenance by assessment rules. A criterion is used for the classification that categorises the equipment due to master data, e.g. age of equipment or design [3].

An additional CAP is the weighted summation that evaluates indicators separately and aggregates them to a condition value by a weighted summation (see fig. 1).

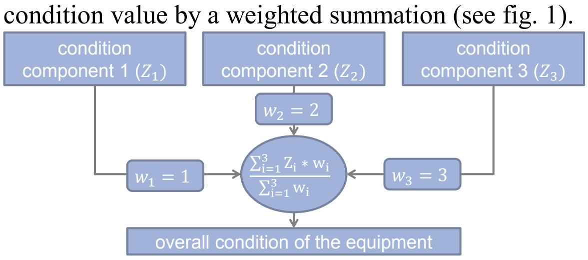

Figure 1: Overview of the weighted summation

The weights w of indicators Z are chosen by maintenance personnel to consider the different importance for the condition [1]. However the capability of humans to make objective judgments is limited to a number of five to nine alternatives [3]. People are therefore overcharged with the rating of more than nine indicators. An objective parameterization of a CAP requires the definition of criteria to evaluate the importance of indicators.

For the ABC method, the equipment is classified according to its impact on non-delivered energy in case of a failure with load interruption. Therefore, the medium voltage equipment is rated the highest because of its effect on the whole medium voltage grid. Subsequently MV/LV transformers are rated as secondary because failures lead to an outage of the complete low-voltage network. For low-voltage equipment only one feeder will be affected while the lowest effect is expected for the station's building because it has no electrical function. Particularly critical hazards, such as access to the MV/LV substations or loss of SF_6-gas are classified as most important which leads immediate action. The classification scheme originates from the maintenance strategy of a German distribution system operator.

For parameterization of the weighted summation, the analytic hierarchy process (AHP) is used to determine objective weights. The AHP is a mathematical method for decision optimization that allows accounting for more than one criterion to evaluate different decisions like the importance of indicators. As relevant criteria, the minor and major failure frequency and functional disturbance in case of malfunction are chosen, because of their influence on the supply reliability. Additionally the repair endurance in case of malfunction is considered to account for the influence of resupply, after an outage occurred. Furthermore, particular urgency for maintenance and the number of affected customers in case of an outage is taken into account. To ensure objectiveness, the medium rates of minor failures calculated from historic events and the repair endurance is estimated by a distribution system operator. Particularly critical failures can be considered by knock-out-rules that lead to the worst possible condition value if any critical failures are ascertained.

Weighting of Indicators by the AHP

The weighting of indicators by the AHP requires an assessment according to defined criteria. For this purpose a score card is used that grades every indicator in every category. The minor and major failure rates and repair endurance are evaluated by the exact values evaluated by statistical analysis. Influence on Functional disturbance, safety and the environment are graded binary due to an evaluation by yes or no. For evaluation of the impact on the grid, ratings from 1 to 4 are used, according to the ABC-process. It is assumed that resupply in case of an outage is finished after three hours at least by mobil generators. Longer duration endurance is graded with equal importance.

Furthermore these criteria are weighted itself by judgement of a distribution system operator to account for their individual importance. This importance might vary according to the distribution operator's concerns. Functional disturbance, safety and environmental impact are considered to be most important. Failure rates are considered to have a learning effect by continues updates of its values. The individual weights of importance criteria are shown in table 2.

Table 2: Weighting of importance criteria

criterion	weight
impact on non-delivered energy	4
personal safety	4
environmental impact	4
failure rates	1
repair endurance	1

In addition to the application of objective criteria, the AHP also allows for an automated generation of weights in dependence on the station's design. The pollution of air insulated switchgear, for example, is graded with higher importance than pollution of hermetically sealed SF_6-switchgear since it can lead to arcing faults. A detailed introduction of the AHP's application can be found in [3].

CONDITION BASED ASSET SIMULATION

To analysis the impact of CAPs and their parameterization, an asset simulation is developed that simulates the development of minor faults, using the example of MV/LV substations. By integration of different CAPs for maintenance planning, economic and technical parameters, such as failure rates and costs of maintenance, can be calculated. It is assumed that substations are inspected in a four years period. Minor faults will develop within two inspections. The simulation uses a discrete grade based system for degradation, in accordance to the inspection protocols. An Overview of the simulation steps are shown in figure 2.

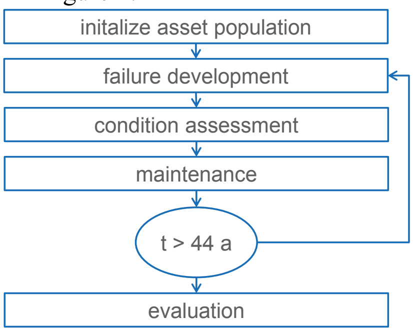

Figure 2: Asset simulation overview

At first the population of MV/LV stations is initialized by setting master data parameters. A dataset of stations is generated in accordance to the population of a German distribution system operator that contains of 38 % building stations, 33 % basement stations, 24 % compact stations and 3% prefabricated stations. 28% of the MV-switchgear is SF_6, 72% is air insulated. In addition 34% of the transformer's sealing ends are insulated while 66% are not. The station's type affects relevant failures. Basement stations for example cannot develop failures of the ceiling and vegetation. Every station is modelled considering every item checked by the inspection protocol, besides type specific irrelevant failures. The population consists of 100 new stations at the simulation's beginning which are assumed have their last inspection at an age of 44 years.

The aim of the asset simulation is to simulate a realistic ageing of a collective of MV/LV stations that degrade in discrete states consecutively from 1 to 4. For the simulation of discrete states, a Markov chain is used. The transition between two states i and j is represented by a transition probability p(i,j). In this specific case, failures develop within four years (see fig 3 a).

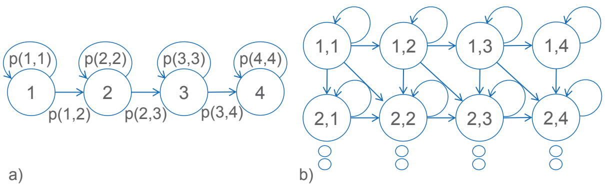

Figure 3: Markov Chain for independent failures a) and two correlating failures b)

Transition rates are calculated on a database of more than 1000 inspection protocols. Degradation is assumed to continue from rating 1 to 4. Possible transitions are to the following or to remain in the current state. A complete Markov chain that considers every possible state of a substation, which is the combination of the 70 protocol items with ratings from 1 to 4, comprises of 24 million states. Because of the needs for statistical data to calculate transition probabilities, the Markov chain is simplified by simulating each protocol item individually. To meet the requirements of realistic conditions, correlating failures with respect to equal causes have to be considered. Therefore the inspection protocols where analyzed for correlating failures using the cross tabulation method, where the statistical independence of occurrence is tested [4]. If the cross tabulation indicates a correlation of faults, a more complex Markov chain is used (see figure 3 b). The disregard of correlating states would lead to a more uniform failure distribution which is less realistic.

After simulation of degradation, the station's conditions are assessed by the ABC-method or weighted summation. Two strategies are considered for maintenance planning. A threshold based approach plans to maintain every station whose condition exceeds a given threshold. Additionally a budget based approach is considered where stations are maintained in order of their condition as long as the budget is sufficient.

EVALUATION OF STRATEGIES

To evaluate maintenance strategies, several performance indicators can be considered. The maintenance costs are calculated by summation of lubricants, man hours and the time to arrive to the MV/LV substations. For the calculation of maintenance costs, an appraisal of the failure specific repair time is provided by a distribution system operator and a service provider for maintenance of electrical equipment. The man-hour costs are assumed to be 60 Euros / hour. In addition, the medium time to arrive to the station is assumed to be 20 minutes. An example of assumed repair times for some medium voltage (MV) equipment is provided by table 3.

Table 3: Exemplarily repair times

	repair time / min		
component	**rating 2**	**rating 3**	**rating 4**
SF_6-pressure	15	90	300
MV housing	30	60	90
MV earthing	90	90	90

Furthermore, the technical consequences have to be evaluated that result from delayed maintenance. Therefore, the failure rate is determined at every inspection. The failure rate is moreover determined for failures with potential to affect the grid's operation, environment or safety of people. Ratings of three and four are counted as failures in accordance to the definition in table 1.

Because of the stochastic deviation of simulation results due to the probabilistic nature of Markov chains, the simulation is repeated several times until the medium value of all performance indicators changes less than one percent over the last five iterations.

SIMULATION RESULTS

The ABC method, weighted summation and the weighted summation without knock-out-rules are applied in a simulation of 100 MV/LV substations to analyse their influence on costs and failure rates. Figure 4 shows an exemplarily result of the simulation using the weighted summation for different thresholds for maintenance.

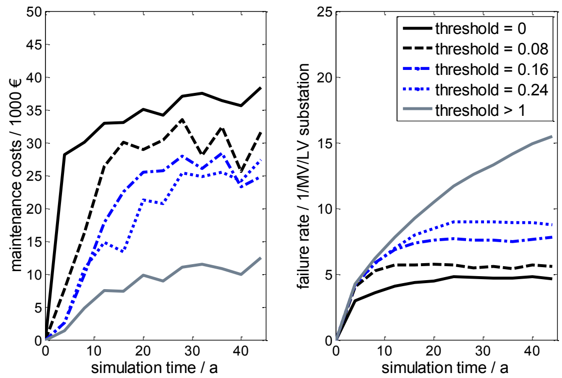

Figure 4: Time-based simulation results with the weighted summation and different thresholds for maintenance

Maintenance costs and the minor failure rates are shown for the complete lifetime of the population. The results show that the costs are decreasing with an increasing threshold while the failure rate rises due to the reduction of maintenance. Because of the definition of a threshold, some failures are not repaired after inspection so that they will further degrade up to higher ratings. The simulation shows that new stations show lesser failures because of the time it takes for failures to develop. Respectively the maintenance costs rise with increasing lifetime.

Figure 5 shows the results of a simulation of different thresholds for the three CAPs. Given are the medium values of costs and failures at inspections. The results show an equal correlation of costs and failures to figure 4. Due to the nature of the ABC process it can only lead to four different condition values leading to steps in costs and failure rates. The weighted summation with and without knock-out-rules can be used for a more finely graduated maintenance planning. At a threshold of nearly 0.4 the weighted summation leads to steady state values for costs and the failure rate because condition values above 0.4 occur rarely. The use of knock-out-rules leads to higher costs and lower failure rates because critical failures are always repaired.

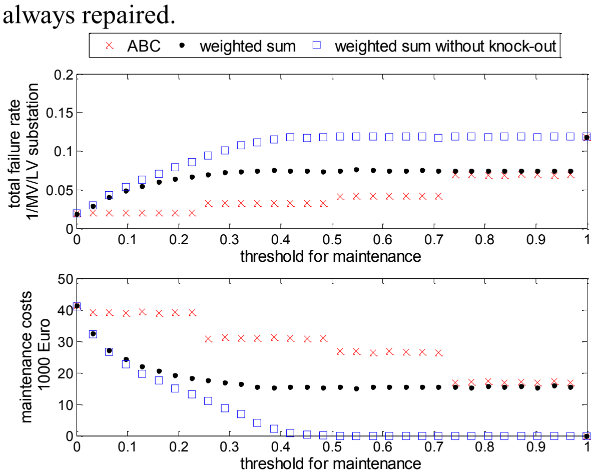

Figure 5: Comparison of CAPs at varying thresholds

Figure 6 shows a comparison of the failure rates with personal safety and network effect at varying budgets. It is shown that for equal costs, the failures with importance for safety and influence on reliability are lower by using the weighted summation for budgets between 0 and 34000 Euros. If enough money is available to maintain all stations, the procedure has no influence on failure rates. The consideration of more importance criteria for the parameterization of the CAP results in lower failure rates for important failures. Due to the fact that the ABC-Method uses the non-delivered energy as it's only criteria, the failure rates are nearly equal because respective faults are preferentially repaired. In addition the failure rate is a little higher at low budgets because the ABC method considers only for faults of rating 3.

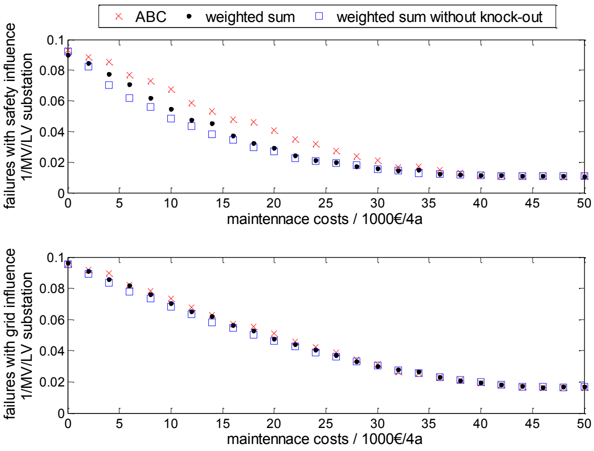

Figure 6: Comparison of CAPs at varying budget

CONCLUSION

Two different condition assessment procedures for MV/LV substations are introduced and applied in a condition based asset simulation. Degradation is simulated by a Markov Chain that calculates failure probabilities in accordance to historical data of failures. The simulation results show the impact of different thresholds for activities on costs of maintenance and failure rates. It is shown that with a reduction of maintenance measures, the technical condition of stations gets worse with increasing age. The assessment procedures and an adaptation of the weighted summation are simulated with varying thresholds and maintenance budget. The results show advantages and disadvantages of the assessment procedures. The weighted summation shows advantages because of the consideration of more criteria than the ABC method and the possibility for finer graduating of condition values.

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